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Examining the consistency of products derived from various ocean color sensors in open ocean (Case 1) waters in the perspective of a multi-sensor approach

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Abstract

During its lifetime, a space-borne ocean color sensor provides world-wide information about important biogeochemical properties of the upper ocean every 2 to 4 days in cloudless regions. Merging simultaneous or complementary data from such sensors to obtain better spatial and temporal coverage is a recurring objective, but it can only be reached if the consistency of the sensor-specific products, as delivered by the various Space Agencies, has first been carefully examined. The goal of the present study is to provide a procedure for establishing a coherency of open ocean (Case-1 waters) data products, for which the various data processing methods are sufficiently similar. The development of the procedure includes a detailed comparison of the marine algorithms used (after atmospheric corrections) by space agencies for the production of standard products, such as the chlorophyll concentration, [Chl], and the diffuse attenuation coefficient, K_d. The MODIS-Aqua, SeaWiFS and MERIS [Chl] products agree over a wide range, between ~0.1 and 3 mg m^{-3}, whereas increasing divergences occur for oligotrophic waters ([Chl] (from 0.02 to 0.09 mg m^{-3}). For the K_d(490) coefficient, different algorithms are in use, with differing results. Based on a semi-analytical reflectance model and hyperspectral approach, the present work proposes a harmonization of the algorithms allowing the products of the various sensors to be comparable, and ultimately, meaningfully merged (the merging procedures themselves are not examined). Additional potential products, obtained by using [Chl] as an intermediate tool, are also examined and proposed. These products include the thickness of the layer heated by the sun, the depth of the euphotic zone, and the Secchi disk depth. The physical limitations in the predictive skill of such downward extrapolations, made from information concerning only the upper layer, are stressed.

Keywords: Ocean color sensors; Chlorophyll; Attenuation coefficient; Multi-sensor products; Products consistency; Heated layer; Euphotic layer; Secchi disk; Merging

1. Introduction

From the perspective of merging data stream delivered by different space-borne ocean color sensors, as advocated by SIMBIOS (1999), and IOCCG (2004) (see list of acronyms, Appendix A), it is necessary to verify that the products to be merged are defined and computed in the same, or at least in compatible, ways. The normalized water-leaving radiance, nLw, or similar quantities, as remote sensing reflectance, R_{rs}, and irradiance reflectance, R (Definitions in Appendix B) are well defined radiometric quantities, and their exact definitions are shared by the cognizant space agencies. This does not mean that the actual products of these agencies are strictly equal or numerically interconvertible. Indeed, uncertainties in calibration (affecting the quantification of the initial signal recorded at the top-of-atmosphere level), then differences in the atmospheric correction schemes (affecting the magnitude of the retrieved marine signals) may introduce some distortions. Such potential divergences are beyond the scope of the present study. In what follows, it will be assumed that these discrepancies or biases, if any, are identified or under control. In such a case, the nLw (or

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similar quantities) from differing data sources are assumed to be consistent within their own uncertainty levels, so that any data merging (including a bias-correcting procedure) can be meaningfully attempted. Note that the merging techniques are out of the scope of the present study; its primary objective is to examine the consistency of two main geophysical products which are derived from the marine signals (supposed to be accurately retrieved).

Specifically, the focus will be on the phytoplankton concentration (or pigment index), generally expressed as chlorophyll concentration (mg m^{-3}), thereafter denoted by [Chl], and on the diffuse attenuation for downward irradiance, K_d (m^{-1}), at a given wavelength (e.g. at 490 nm). These products are computed using algorithms which manipulate, in various manners, the radiometric spectral signals as retrieved at the sea level. Most of these algorithms (in particular those examined here) have been established for, and are only pertinent to, Case-1 waters. For historical reasons, however, (in particular because of the use of differing channel combinations, distinct scientific approaches, as well as independent field data bases), these algorithms differ to an extent which deserves examination. The ocean color algorithms considered here are those which are the operationally validated algorithms, in use with SeaWiFS, MODIS-Aqua (MODIS-A), and MERIS (next re-processing), and routinely providing global products. As a complementary objective, the possibility of using [Chl] and K_d for tentative predictions of the heat deposition, the euphotic layer depth, and the Secchi disk depth are also examined.

It is worth noting that the derivation of other products, not restricted to Case-1 waters, is presently under investigation (see e.g., IOCCG, 2000, 2006; Lee et al., 2002, 2005; Loisel et al., 2002; Maritorena et al., 2002). These on-going studies aim at retrieving additional geophysical products, such as the concentrations of colored dissolved organic matter and of suspended sediments, or some inherent optical properties of the water body, such as the absorption and the backscattering coefficients. They are at the root of bio-optical model-based merging techniques (Maritorena & Siegel, 2005). These new products and various proposed methodologies are out of the scope of the present study, which is restricted to the examination of the coherency of the data streams, as they are routinely produced by satellite missions.

5. Conclusions and perspectives

The present study was restricted to the examination of divergences resulting only from the use of differing algorithms for the retrieval of [Chl] and K_d. Indeed, the same initial marine signals (radiances or reflectances) have been successively introduced into the various algorithms for a comparison of the outputs. As stressed at the beginning, differences in the products as delivered by space agencies may differ for other reasons (signal calibration at the top of atmosphere, atmospheric correction schemes), which were not examined here. One part of the differences in the final products, however, originates only from the marine algorithm diversity, and it is essential to quantify separately the magnitude of this impact.

With respect to the [Chl] retrieval, the algorithms presently in use are not totally coincident, particularly in the domain of low concentration. There is presently no decisive argument, however, to select one algorithm over another one among those available. The empirical algorithms developed for SeaWiFS and MODIS-A are based on the same R_{rs} vs [Chl] dataset (basically NOMAD and posterior data); they also have been adjusted to make them as compatible as possible. The semi-analytical algorithm developed for MERIS also involves field data (for K_d vs [Chl]), but this dataset is completely independent from the NOMAD database. It is extremely reassuring that these two differing approaches (as well as the two datasets) lead to convergent results, at least over most of the [Chl] range.

In the future perspective of merging data from various sensors, however, the divergence of the returns at the extreme ends of the [Chl] range may pose a problem. Using specific algorithms tuned for each sensor (i.e., for each band setting), but all deriving from the same hyperspectral bio-optical model is probably a convenient tool to get a sensor-independent product. Along this line, the set of OC4Me, OC4Me555, and OC3Me550 algorithms would satisfy this requirement. Such a choice, however, can always be contested, but less disputable is the resulting consistency. Actually, and if another choice is made, the reversibility is always possible and easy. Indeed, the relationships graphically displayed in Fig. 2b are pivotal (5th order polynomials in both directions available on request), for they allow inter-convertibility and easy reversibility of the [Chl] products.

With respect to the K_d(490) coefficient, and its immediate derivative (the K(PAR) coefficient), a unified solution is also desirable. The historical approach based on a ratio of remote sensing reflectances implies that several algorithms are specifically developed for each sensor (and band setting), which in turn implies that enough data are available for the specific wavelengths 550, 555, and 560 nm. Assuming that such a requirement is fulfilled, the application of a more realistic curvilinear algorithm (of the OK2 type) is preferable to the use of purely empirical (linear) expressions which induce systematic errors. The use of [Chl] as an intermediate link is another solution (actually is a solution close to that offered by OK2), which presents the advantage of ensuring an overall consistency between the sensors products (once the [Chl] differences are resolved). The validity of this approach is reinforced by the coincidence of the two datasets (NOMAD and LOV), which allows their merging and the production of a highly significant relationship between K_d(490) and [Chl]. Another benefit lies in the fact that K_d coefficients at wavelengths other than 490 nm (Table 4), as well as K(PAR), can be produced in the same way. The applicability of such methods, however, is restricted to Case-1 waters only; for more complex waters and higher K_d values, other approaches (e.g. Lee et al., 2005) must be envisaged.

Those products which can also be derived from the chlorophyll concentration (in Case-1 waters), such as the thickness of the solar heated layer, the euphotic depth, and the Secchi disk depth, could be produced at the level of individual sensors, or as well by using the merged [Chl] products of these sensors. In addition to natural variability, the predictive capabilities of the algorithms providing these quantities are limited by the uncertainties linked to the assumptions needed for the downward extrapolations.